Acta Astronautica 90 (2013) 146–155

Contents lists available at SciVerse ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Hypervelocity nuclear interceptors for asteroid disruption

B. Wie*

Vance Coffman Endowed Chair Professor, Asteroid Deflection Research Center, Department of Aerospace Engineering, Iowa State University, Ames, IA 50011, United States

ARTICLE INFO

Article history:
Received 14 February 2012
Accepted 16 April 2012
Available online 5 May 2012

Keywords:
Planetary defense
NEO
Hypervelocity nuclear interceptors
Kinetic impactors
Gravity tractors

ABSTRACT

A direct intercept mission with nuclear explosives is the only practical mitigation option against the most probable impact threat of near-Earth objects (NEOs) with warning times much shorter than 10 years. However, state-of-the-art penetrating subsurface nuclear explosion technology limits the penetrator's impact velocity to less than approximately 300 m/s because higher impact velocities prematurely destroy the nuclear fusing mechanisms. Therefore, significant advances in hypervelocity nuclear interceptor/penetrator technology are required to enable a last-minute nuclear disruption mission with intercept velocities as high as 30 km/s. This paper briefly describes both the current and planned research activities at the Iowa State Asteroid Deflection Research Center for developing such a game-changing space technology to mitigate the most probable impact threat of NEOs with a short warning time.

1. Introduction

A growing interest currently exists for developing a plan to protect the Earth from the future possibility of a catastrophic impact by a hazardous asteroid or comet. In a recent letter on NEOs from the White House Office of Science and Technology Policy (OSTP) to the U.S. Senate and Congress, the White House OSTP strongly recommends that NASA takes the lead in conducting research activities for the development of NEO detection, characterization, and deflection technologies [1]. Furthermore, President Obama's new National Space Policy specifically directs NASA to "pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalog, and characterize NEOs to reduce the risk of harm to humans from an unexpected impact on our planet." The Planetary Defense Task Force of the NASA Advisory Council also recommended that the NASA Office of the Chief Technologist (OCT) begin efforts to investigate asteroid deflection techniques. With national interest growing in the United States, the NEO threat detection and mitigation problem was recently identified as one of NASA's Space Technology Grand Challenges.

The Asteroid Deflection Research Center (ADRC) at Iowa State University has been developing strategies and technologies for deflection or disruption of hazardous NEOs. As the first university research center in the United States dedicated to such a complex engineering problem, the ADRC was founded in 2008 to address the engineering challenges and technology development critical to NEO impact threat mitigation.

Although various NEO deflection technologies, such as nuclear explosions, kinetic impactors, and slow-pull gravity tractors (GTs), have been proposed during the past two decades, there is no consensus on how to reliably deflect or disrupt hazardous NEOs in a timely manner [2–6]. Furthermore,due to various uncertainties in asteroid detection and tracking, the warning time before an asteroid impact with the Earth can be very short. All of the non-nuclear techniques, including hypervelocity kinetic impactors and slow-pull GTs, require mission lead times much longer than 10 years, even for a relatively small NEO. However, the most probable mission scenarios will have a warning time much shorter than 10 years, so the use of higher-energy nuclear

* Tel.: +1 515 294 3124.
E-mail address: bongwie@iastate.edu

0094-5765/$ - see front matter © 2012 IAA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actaastro.2012.04.028

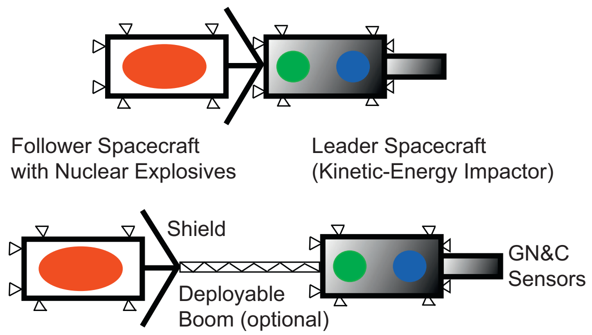

Fig. 1. Conceptual illustration of a two-body hypervelocity nuclear interceptor (HNI) system, which is currently being further examined through the NIAC (NASA Innovative Advanced Concept) Phase 1 program (2011–2012) of the NASA Office of the Chief Technologist.

explosives in space will become inevitable. Staging direct intercept missions with a short warning time will result in arrival velocities of 10–30 km/s with respect to target asteroids. A rendezvous mission to a target asteroid, requiring an extremely large arrival ΔV of 10–30 km/s, is totally impractical.

Although a less destructive standoff nuclear explosion can be employed for deflection missions, the momentum/energy transfer created by a shallow subsurface nuclear explosion is at least 100 times larger than that of an optimal standoff nuclear explosion. However, state-of-the-art nuclear subsurface penetrator technology limits the impact velocity to less than about 300 m/s because higher impact velocities prematurely destroy the penetrating fusing mechanisms. An impact speed limit of 1.5 km/s has been cited for nuclear Earth-penetrator weapons (EPWs) in [7]. Neither a precision standoff explosion at an optimal height of burst (HOB) near an irregularly shaped, smaller NEO, with intercept velocities as high as 30 km/s, nor a contact burst is a trivial engineering task.

Consequently, a hypervelocity nuclear interceptor (HNI) system concept is proposed in this paper, which will enable a last-minute, nuclear disruption mission with intercept velocities as high as 30 km/s. The proposed system employs a two-body space vehicle consisting of a fore body (leader) and an aft body (follower), as illustrated in Fig. 1. The leader spacecraft provides proper kinetic-impact crater conditions for the follower spacecraft carrying nuclear explosive devices (NEDs) to make a robust and effective explosion below the surface of a target asteroid body. Surface contact burst or standoff explosion missions may not require such a two-body vehicle configuration. However, for a precision standoff explosion at an optimal HOB, accurate timing of the nuclear explosive detonation will be required during the terminal phase of hypervelocity intercept missions. Robust nuclear disruption strategies and technologies, to be employed in a last-minute, direct intercept mission, should be further studied, developed, and flight tested/validated.

2. Non-nuclear options

The physical principles behind, as well as some practical limitations of, non-nuclear options, such as gravity tractors and kinetic impactors, will be briefly discussed in this section.

2.1. Gravity tractors

Lu and Love [4] have proposed a low-energy asteroid deflection concept utilizing the mutual gravitational force between a hovering spacecraft and a target asteroid as a towline, as illustrated in Fig. 2. To avoid exhaust plume impingement on the asteroid surface, two ion engines are properly tilted outward and the hovering distance is accordingly selected as: $d=1.5r$ and $\phi=20^\circ$. This illustrative combination yields an engine cant angle of 60°, and the two tilted thrusters (each with a thrust T) then produce a total towing thrust T as illustrated in Fig. 2. A simple spherical body is considered here for conceptual illustration without loss of generality.

Although a large 20-ton gravity-tractor (GT) spacecraft propelled by a nuclear-electric propulsion system is needed for somewhat realistic circumstances [4], a smaller 1000-kg GT spacecraft is capable of towing a certain class of NEOs, such as asteroid 99942 Apophis, with the so-called keyhole property [5]. It is interesting to notice that such a gravitational coupling/towing concept has been previously proposed for somewhat science-fictional, astronomical problems by Shkadov in 1987, and also by McInnes in 2002, as discussed in [5].

To illustrate the principle behind the GT concept, we consider here a simplified dynamical model of the GT for towing asteroid Apophis (with an assumed diameter of 320 m), given by

$$M\frac{\Delta V}{\Delta t}=\frac{GMm}{d^2}=T \tag{1}$$

or

$$\frac{\Delta V}{\Delta t}=\frac{Gm}{d^2}=\frac{T}{M}=A \tag{2}$$

where $G=6.6695\times10^{-11}$ N m^2/kg^2, $M=4.6\times10^{10}$ kg, $m=1000$ kg, $r=160$ m, $d=240$ m, $T=0.053$ N, $A=1.1579\times10^{-9}$ mm/s^2 is the characteristic acceleration, and

$$\Delta V=A\Delta t \tag{3}$$

$$\Delta X=\frac{1}{2}A(\Delta t)^2 \tag{4}$$

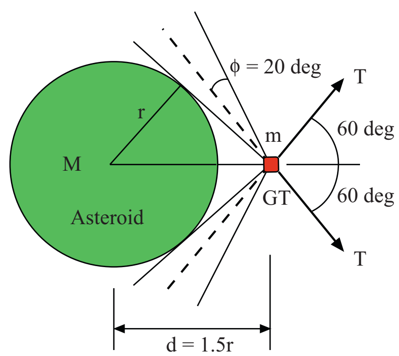

Fig. 2. A geometrical illustration of the gravity tractor (GT) concept for towing an asteroid.

where ΔV and ΔX are, respectively, the resulting velocity and position changes for the total towing period of Δt. For example, we have $\Delta V = 0.036$ mm/s and $\Delta X = 575$ m for $\Delta t =$ one year.

Including the orbital "amplification" effect [5], we have

$$\Delta V = 3A\Delta t \tag{5}$$

$$\Delta X = \frac{3}{2}A(\Delta t)^2 \tag{6}$$

Consequently, we have $\Delta V = 0.1$ mm/s and $\Delta X = 1.7$ km for a one-year towing of Apophis by a 1000-kg GT.

Including an additional coasting time of t_c, we have the total position change (i.e., the Earth-miss distance), given by [5]

$$\Delta X = \frac{3}{2}A\Delta t(\Delta t + 2t_c) \tag{7}$$

Thus, a one-year towing of Apophis in 2026, with an additional 3 years of coasting time, will cause a total orbital deflection of approximately 12 km in 2029. This may be considered sufficient to safely move Apophis out of its 600-m keyhole in 2029. However, it is important to note that any NEO deflection effort must produce an actual orbital change much larger than predicted orbital uncertainties from all perturbation sources, including the Yarkovsky effect.

A 1000-kg GT spacecraft equipped with ion engines can only be considered a viable option only for special cases, like a pre-2029 deflection mission for Apophis. Furthermore, it is emphasized that a 1000-kg spacecraft, colliding with Apophis at a modest impact velocity of 10 km/s in 2026, will cause a much larger instantaneous velocity change of at least 0.22 mm/s for Apophis, resulting in an orbital deflection of 62 km in 2029. In general, the gravity tractor is not applicable to other situations without keyholes.

2.2. Kinetic impactors

A non-nuclear approach does currently exist for an impulsive velocity change, caused by targeted kinetic impact of a spacecraft on the target asteroid's surface. If applied correctly, that is, without causing fragmentation of a large asteroid into smaller pieces and applied long enough prior to an expected Earth impact, the effect of such an impulsive ΔV would magnify over decades (or even centuries), eliminating the risk of collision with Earth. To be most effective, the impacting spacecraft would either have to be massive, or be moving very fast relative to the asteroid. Since a current launch technology limits the mass (including propellant) that can be lifted into an interplanetary trajectory, we are therefore led to consider designs that would maximize impact velocity, and which would not require large amounts of fuel.

The success of NASA's Deep Impact mission in 2005 significantly enhanced the practical viability of the kinetic-impactor concept. Its mission goals were to explore the internal structure and composition of the nucleus of comet Tempel 1 before, during, and after impact, and to return the observations to Earth. The Deep Impact spacecraft was launched by a Delta II launch vehicle on January 12, 2005 and released a 370-kg impactor spacecraft, which collided with Tempel 1 on July 4, 2005 to create a large crater on the surface of the 5-km target comet, as shown in Fig. 3. The crater is estimated to be 20-m deep and 100-m wide. In fact, the 5-km comet, with a heliocentric speed of 29.9 km/s, crashed into the 370-kg impactor, which was moving at a slower heliocentric speed of 22.4 km/s. This resulted in a rear-end collision of the impactor spacecraft at a 10 km/s impact speed at an impact approach angle of 15°, as illustrated in Fig. 4(a). The kinetic energy of the impactor was 1.9×10^{10} J and the resulting impact ΔV was practically zero. The Deep Impact mission was not intended to deflect the orbit of such a large 5-km comet. The attitude/position of the impactor spacecraft after being released from the flyby spacecraft was precisely controlled by the autonomous optical navigation system to achieve a 300-m targeting accuracy.

The European Space Agency once envisioned a small kinetic-energy impactor precursor mission concept (named the Don Quijote mission) targeted for a 500-m asteroid. The Don Quijote mission consists of two nearly identical spacecraft: an orbiter (Sancho) and an impactor (Hidalgo). Its overall mission objective is to measure the actual

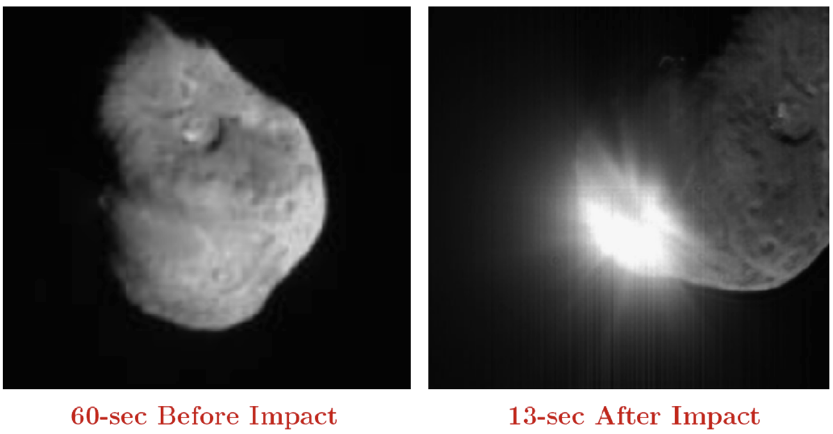

Fig. 3. Deep Impact mission. Image Courtesy of NASA/JPL-Caltech/UMD.

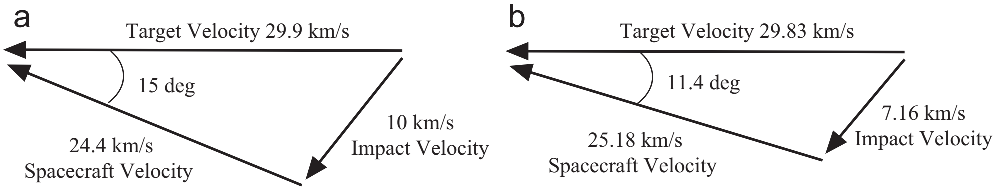

Fig. 4. Impact velocities of kinetic impactors.

translational/rotational momentum transfer of the impact, impact crater/ejecta, and surface/internal properties before/after impact. The orbiter Sancho will be launched first. It will rendezvous with the asteroid for target asteroid orbit determination, and to measure mass, size, gravity, and surface properties. After a successful orbiter mission at the asteroid, the impactor Hidalgo will be launched from Earth. Similar to the Deep Impact mission, a target asteroid with a 29.83 km/s heliocentric speed will crash into an impactor spacecraft moving at a 25.18 km/s heliocentric speed. This will result in a rear-end collision of the impactor spacecraft at an impact velocity of 7.16 km/s with an impact approach angle of 11.4°, as illustrated in Fig. 4(b). The resulting impact ΔV will be very small (less than 0.01 cm/s), but it is expected to be sufficient to achieve a 100-m change in the semimajor axis that can be measured with 10% accuracy. To mitigate the real threat of NEOs in the future, a separate inspection mission similar to Deep Impact or Don Quijote may be required as an integral part of any large-scale space mission of deflecting/disrupting NEOs.

NASA's most recent impactor endeavor was the Lunar Crater Observation and Sensing Satellite (LCROSS) mission, designed to investigate the possibility of water on the moon. LCROSS was launched in June 2009, in conjunction with the Lunar Reconnaissance Orbiter (LRO), as part of the Lunar Precursor Robotic Program. For this mission, LCROSS did not carry a sophisticated impactor spacecraft; rather it used an SUV-sized Centaur booster rocket from the Atlas V launch vehicle, as illustrated in Fig. 5. The Centaur booster rocket was successfully fired at the Cabeus crater at the lunar South Pole, with an estimated velocity of 2.78 km/s. The impact was expected to form a crater of 20 m in diameter and 4 m deep, and excavate more than 350 Mt of lunar regolith with a plume as high as 10 km from the surface. Four minutes after the Centaur impact, the LCROSS spacecraft followed the impactor through the dust plume to determine the composition of the ejected material and relay the information back to Earth.

The simplest deflection approach is to impact the target NEO with a massive projectile at a high relative speed. However, a successful asteroid deflection mission will require accurate modeling and prediction of the change in velocity caused by the interceptor's impact. The effective impulse imparted to the asteroid will be the sum of the pure kinetic impulse (linear momentum) of the interceptor, plus the impulse due to the thrust of material being ejected from the impact crater. This last term can be significant (even dominant in some cases), but its magnitude depends strongly upon the density and yield strength of the material the asteroid is composed of, as well as the mass and relative velocity of the interceptor.

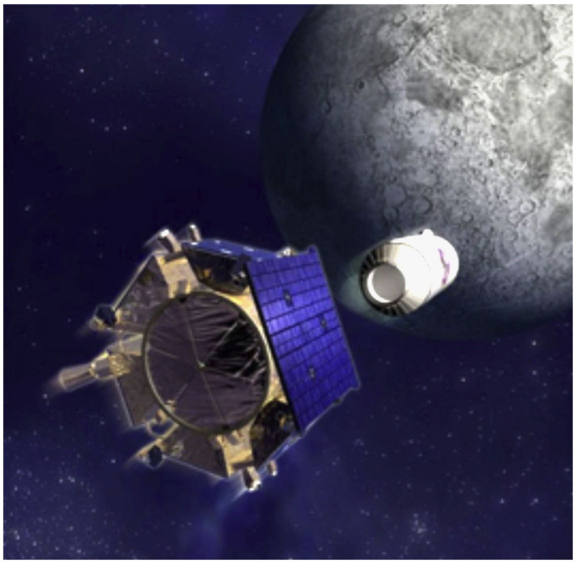

Fig. 5. Illustration of NASA's LCROSS mission using the Centaur booster rocket as a kinetic impactor toward the moon in 2009. Image courtesy of NASA.

Using the principle of conservation of linear momentum, we can estimate the resulting impact ΔV (the instantaneous velocity change of the target asteroid) as

$$\Delta V \approx \beta \frac{m}{M+m} U \approx \beta \frac{m}{M} U \tag{8}$$

where β is the impact efficiency factor ($\beta = 1$ for an ideal inelastic impact), m the impactor mass, M the target asteroid mass, and U the relative impact velocity.

For example, a head-on collision (at a relative velocity of 70 km/s) of a150-kg impactor on a 200-m, S-class asteroid (with a density of 2720 kg/m^3 and a mass of 1.1×10^{10} kg) results in a pure kinetic-impact ΔV of approximately 0.1 cm/s [3]. If the asteroid is composed of hard rock, then the modeling of crater ejecta impulse would predict an additional ΔV of 0.2 cm/s, which is double the pure kinetic-impact ΔV, resulting in $\beta = 3$. However, if the asteroid were composed of soft rock, previous studies predict an additional ΔV of 0.55 cm/s, which is more than five times the pure kinetic-impact ΔV, resulting in $\beta = 6.5$. Thus, accurate modeling and prediction of ejecta impulse for various asteroid compositions is a critical part of kinetic-impact approaches. More studies are needed to allow us to substantially improve the accuracy of these predictions, especially for high-velocity impacts, and also to extend to cases where the impact area is composed of ice or lunar-type regolith, as well as

to cases where the asteroid is a porous rubble pile. Furthermore, the cratering efficiency could be improved through the use of a small conventional explosive payload, an option that would likely require tradeoffs in impactor design and mission architecture.

For an impulsive ΔV change along the orbital direction, the resulting deflection Δx after a coasting time of t_c can be estimated as

$$\Delta x \approx 3 t_c \Delta V \tag{9}$$

for an asteroid in a near circular orbit. For example, an impulsive ΔV of 1 cm/s will be required for a kinetic impactor mission to result in a deflection distance of 9460 km after a coasting time of 10 years. However, it will be a technically challenging problem to design a kinetic impactor mission to produce an impact ΔV of much larger than 1 cm/s when the warning time is much shorter than 10 years.

2.3. Gravitational binding energy

A practical concern of the kinetic-impact or nuclear approach to mitigating the threat of asteroids is the risk that the impact could result in fragmentation of the asteroid, which could substantially increase the damage upon Earth impact. The energy required to fragment an asteroid depends critically upon the asteroid's size, composition, and structure.

In astrophysics, the energy required to disassemble a celestial body consisting of loose material, which is held together by gravity alone, into space debris such as dust and gas is called the gravitational binding energy.

The gravitational binding energy of a spherical body of mass M, uniform density ρ, and radius R is given by

$$E = \frac{3GM^2}{5R} = \frac{3G}{5R}\left(\frac{4\pi\rho R^3}{3}\right)^2 = \frac{\pi^2\rho^2 G}{30} D^5 \tag{10}$$

where $G = 6.67259 \times 10^{-11}$ N m^2/kg^2 is the universal gravitational constant and $D = 2R$ is the diameter of a spherical body. The escape speed from its surface is given by

$$V_e = \sqrt{\frac{2GM}{R}}$$

For example, for a 200-m (diameter) asteroid with a uniform density of $\rho = 2720$ kg/m^3 and a mass of $M = 1.1 \times 10^{10}$ kg, the gravitational binding energy is estimated to be 4.8×10^7 J. Since the kinetic energy of a 150-kg impactor at an impact velocity of 70 km/s is 3.7×10^{11} J, one may expect that a gravity-dominated, 200-m asteroid would be disrupted and dispersed by such a high-energy impactor. However, its escape velocity of 12 cm/s is about 120 times the impact ΔV of 0.1 cm/s. This large ratio of escape velocity to impact ΔV suggests that if the asteroid disperses, the resulting fragments might scatter around their deflected center of mass.

In [8,9], the disruption energy per unit asteroid mass is predicted to be 150 J/kg for strength-dominated asteroids. This indicates that a strength-dominated, 200-m asteroid would not be disrupted by a 150-kg impactor at a high impact velocity of 70 km/s. Also in [9], the energy (per unit asteroid mass) required for both disruption and dispersion of a 1-km asteroid is predicted to be 5 kJ/kg. Thus, the feasibility of the most kinetic-impact approaches for either disrupting or deflecting an incoming NEO depends on the NEO's size and composition (e.g., solid body, porous rubble pile, etc.), as well as the time available to change its orbit. An accurate determination of the composition of the target asteroid is a critical part of the kinetic-impact approaches, which may require a separate inspection mission.

A further study is also needed to optimize impactor size, relative impact velocity, and the total number of impactors as functions of asteroid size and composition, to ensure a deflection attempt does not cause unintended fragmentation.

3. Nuclear options

In practice, deflection methods of sufficiently high-energy density are preferred and need to be prepared in advance of an expected impact date with the Earth. One of these methods utilizes a nuclear explosion at a specified standoff distance from the target NEO, to effect a velocity change by ablating and blowing off a thin layer of the surface. The basic physical fundamentals of such nuclear standoff explosions can be found in [8–10].

Nuclear standoff explosions are often assessed to be much more effective than the non-nuclear alternatives, especially for larger asteroids with a short mission lead time. Other techniques involving the use of surface or subsurface nuclear explosives are also assessed to be more efficient, although they may cause an increased risk of fracturing the target asteroid. However, the nuclear approach needs more rigorous studies to verify its overall effectiveness and determine its practical viability. Nuclear standoff explosions require an optimal standoff distance for maximum velocity change of a target asteroid. Therefore, we have to determine how close the nuclear explosion must be to effectively change the orbital trajectories of asteroids of different types, sizes, and shapes. The precise outcome of an NEO deflection attempt using a nuclear standoff explosion is dependent on myriad variables. Shape and composition of the target NEO are critical factors. These critical properties, plus others, would need to be characterized, ideally by a separate mission, prior to a successful nuclear deflection attempt. High-fidelity physical models to reliably predict the velocity change and fragmentation caused by a nuclear standoff explosion will need to be developed.

A simple model that can be used to assess the effectiveness of a nuclear standoff explosion approach was examined in [10]. Geometric principles and basic physics were used in [10] to construct a simple model which can be augmented to account for icy bodies, anisotropic ejecta distributions, and effects unique to the nuclear blast model. Use of this simple model has resulted in an estimation of NEO velocity change of about 1 cm/s on the same order as other complex models, and data correlation suggests an optimal standoff distance of about 200 m for an ideal spherical model of a 1-km NEO. A summary of the deflection ΔV performance characteristics of a nuclear standoff explosion is provided in Fig. 6 [10]. More rigorous physical modeling and simulation, including hydrodynamic codes and other forms of computer

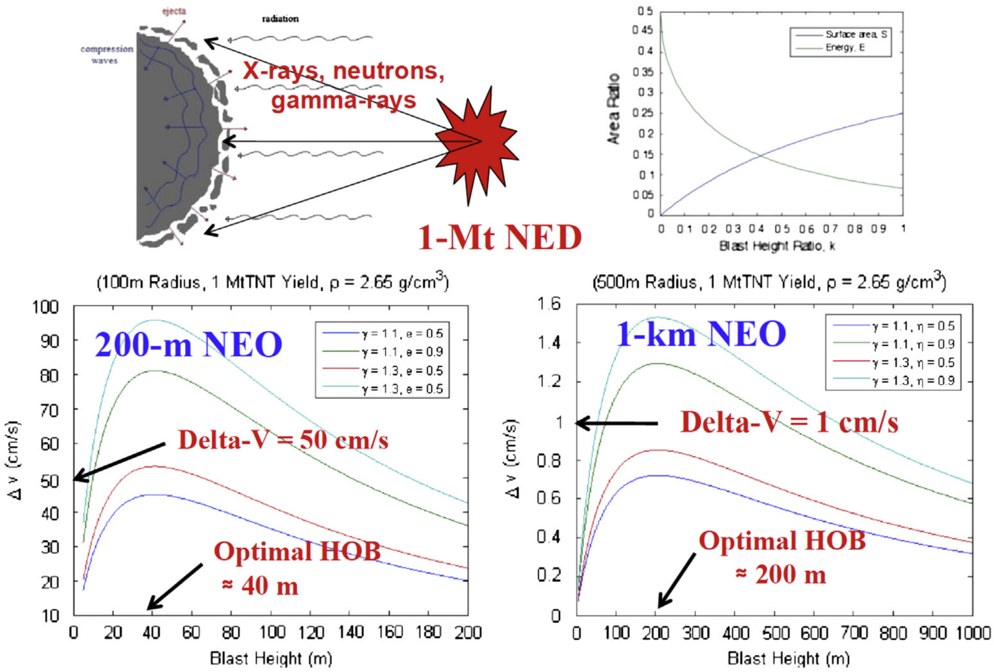

Fig. 6. A summary of the ideal deflection ΔV performance characteristics of a standoff nuclear explosion [10].

modeling, will be necessary to account for changes in material properties under the realistic conditions of the nuclear blast. Possible fracturing of the asteroid and other anticipated outcomes of a nuclear blast are also needed for a further study.

If an NEO on an Earth-impacting course is detected with a short warning time (e.g., much less than 10 years), the challenge becomes how to mitigate its threat in a timely manner. For a small asteroid impacting in a sufficiently unpopulated region, mitigation may simply involve evacuation [6]. However, for larger asteroids, or asteroids impacting sufficiently developed regions, the threat may be mitigated by either disrupting the asteroid (i.e., destroying or fragmenting with substantial dispersion), or by altering its trajectory such that it will either avoid impacting the predicted impact location, or miss the Earth entirely. When the time before impact with the Earth exceeds a decade, the velocity perturbation needed to alter the orbit is relatively small ($\approx 1-2$ cm/s). A variety of schemes, including nuclear standoff or surface explosions, kinetic-energy impactors, and slow-pull gravity tractors, can be employed for such cases. The feasibility of each approach to deflect an incoming hazardous NEO depends on size, spin rate, composition, the mission lead time, and many other factors. When the time to impact with Earth is short, the necessary velocity change of a target NEO becomes extremely large.

To date, kinetic-energy impactors or nuclear explosions are the most mature technologies for asteroid deflection or disruption. Both approaches are impulsive and energy-rich, in that the final momentum change can be considerably more than that present in the original impactor, or in the expanded vaporization layer (from a nuclear explosion). Both methods are expected to eject some debris, and the amount depends on surface material properties. High porosity affects the ability to convert the excess energy into additional momentum. Some asteroids like Itokawa have been determined to have densities (and thus porosities) comparable to terrestrial material with well-characterized shock propagation. Others appear to have very low porosity that may absorb excess energy without the hydrodynamic rebound that can amplify the original impulse.

Because nuclear energy densities are nearly a million times higher than those possible with chemical bonds, a nuclear device is the most mass-efficient means for storing energy with today's technology. Consequently, even in standoff mode, a nuclear explosion is much more effective than any other non-nuclear alternative, especially for larger NEOs with a short mission lead time. It is again important to note that any NEO deflection/disruption effort must produce an actual orbital change much larger than predicted orbital perturbation uncertainties from all sources. Likewise, any NEO deflection/disruption approach must be robust against the unknown material properties of a target NEO.

Another nuclear technique, involving the use of subsurface nuclear explosives, is in fact more efficient than the standoff explosion. The nuclear subsurface method, even with shallow burial to a depth of 3–5 m, delivers a large amount of energy, so that there is a likelihood of totally disrupting the NEO. A common concern for such a powerful nuclear option is the risk that the deflection mission could result in fragmentation of the NEO, which could substantially increase the damage upon Earth impact. In fact, if the NEO breaks into a small number of large fragments but with very small dispersion speeds, the multiple impacts on Earth might cause far more damage than a single, larger impact.

However, despite the uncertainties inherent to the nuclear disruption approach, disruption can become an effective strategy if most fragments disperse at speeds in excess of the escape velocity of an asteroid so that a very small fraction of fragments impacts the Earth. When the warning time is very short, disruption is the only feasible strategy, especially if all other deflection approaches were to fail, as was concluded in [6].

4. Hypervelocity nuclear interceptor (HNI) concept

In the mid-1990s, researchers at the Russian Federal Nuclear Center examined a conceptual configuration design of a rigidly connected, two-segment nuclear penetrator system as illustrated in Fig. 7 [11]. Because this configuration, even with a fore segment equipped with a shaped charge, limited the impact velocity to less than 1.5 km/s, researchers at the Central Institute of Physics and Technology in Moscow, Russia also conducted a preliminary simulation study of a concept for a high-speed penetrating subsurface nuclear explosion [12]. The concept employed a fore body followed by an aft body (carrying nuclear explosives), allowing an impact velocity of 30 km/s. The fore body impacts the asteroid surface first, creating a large crater, followed by the aft body, which penetrates to a depth of three meters. However, a further simulation of a nuclear subsurface explosion and a detailed system-level design were not discussed in [12]. It is now time to further examine this concept to develop a technically feasible option for mitigating the impact threat of NEOs with a short warning time.

A preliminary conceptual design of an interplanetary ballistic missile (IPBM) system carrying a nuclear interceptor has been conducted at the ADRC [13,14]. The proposed IPBM system consists of a launch vehicle (LV) and an integrated space vehicle (ISV), as illustrated in Fig. 8. The ISV consists of an orbital transfer vehicle (OTV) and a terminal maneuvering vehicle (TMV) carrying NED payloads. A Delta IV Heavy launch vehicle can be chosen as a baseline LV for a primary IPBM system for delivering a 1500-kg ($\approx$2-Mt yield) NED for an intercept mission against a target NEO. A secondary IPBM system using a Delta II class launch vehicle (or a Taurus II), with a smaller ISV carrying a 500-kg (500-kt yield) NED, is also described in [13,14]. An OTV can be used as the fore body KEI spacecraft when a TMV is the aft body spacecraft carrying NEDs.

The terminal-phase guidance and control of a two-body HNI system, consisting of two separate formation-flying spacecraft, presents a technically challenging problem, involving high impact velocities (up to 30 km/s) and small, faint targets. A successful rendezvous mission, for flyby or

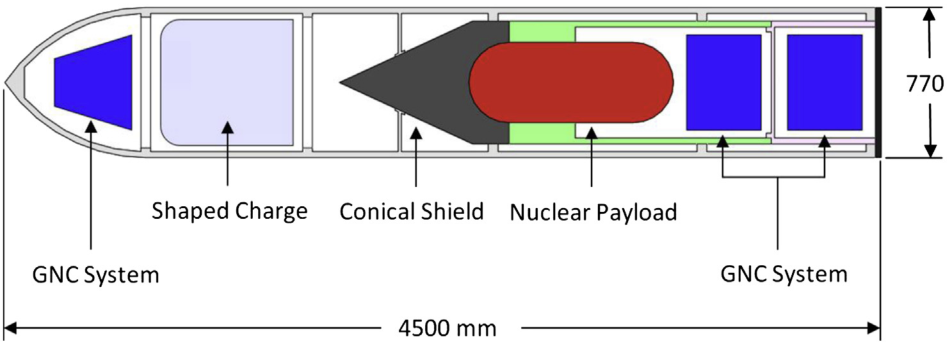

Fig. 7. Conceptual illustration of a two-segment nuclear penetrator system proposed by Russian scientists in 1997, which still limited the impact velocity to less than 1.5 km/s [11].

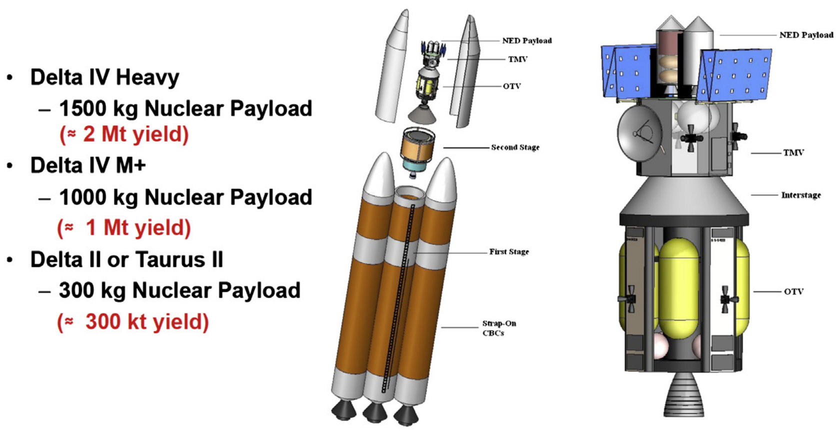

Fig. 8. Illustration of a proposed IPBM system architecture [13].

proximity operations, can approach a target asteroid from any angle. However, precision interceptor missions may require impact-angle control for impact at a specified angle. Communications with Earth may not be feasible during the terminal phase, so the control scheme must rely on onboard measurements and computations [15,16]. The combination of a high velocity and a small target means that an effective guidance system will require only optical measurements. Recent work shows that the trajectories of fragments from a nuclear explosion, and the eventual impact locations on the Earth, of the dispersed fragments depend significantly on the impact angle of the interceptor [17–19]. Attaining the desired impact angle while still successfully achieving impact is crucial for a successful nuclear deflection/disruption attempt.

The current study effort at the ADRC will provide requirements for and limitations on the intercept mission, including maneuvering fuel requirements, interceptor design, relative impact velocity, and GN&C sensors. Every potentially hazardous NEO will have different orbital characteristics and composition. This research will identify which factors affect angle-constrained terminal-phase guidance, and what strategies to employ for a variety of scenarios. Most current space missions do not require a specific encounter angle to be commanded in the terminal phase. Instead, the encounter angle is chosen as a consequence of the orbit the spacecraft follows from the Earth. Maneuvering thrusters are not typically used to significantly change the trajectory of the spacecraft near encounter with an object, but rather to make small adjustments to make the actual trajectory match the nominal mission trajectory. The current study will evaluate the feasibility of implementing practical control laws on interceptor spacecraft for real missions, namely high-speed intercept missions with angle-of-impact constraints enforced in the terminal phase with precision targeting requirements.

It is important to note that the Deep Impact mission has validated the kinetic-impact technology for a relatively large, 5-km target body at an impact speed of 10 km/s in reasonably good lighting conditions. Precision targeting of a smaller (e.g., <500 m), irregularly shaped target asteroid with an impact speed of up to 30 km/s in worst-case circumstances needs to be flight tested/validated/demonstrated in the near future.

An asteroid approximately the size of the asteroid Apophis is considered as a reference target asteroid in [17]. The model asteroid has a total mass of 2.058E13 kg with a diameter of 270 m. An ideal nuclear subsurface explosion of this model was developed by Dr. David Dearborn at Lawrence Livermore National Laboratory. This ideal model assumed a subsurface explosion in a cylindrical region below the surface of the body by sourcing in energy corresponding to 300 kt. It assumed a two-component (inhomogeneous) spherical structure with a high density (2.63 g/cm^3) core, consistent with granite, and a lower density (1.91 g/cm^3) mantle. The bulk density of the structures was 1.99 g/cm^3, close to that measured for asteroid Itokawa (density = 1.95 g/cm^3). The energy source region expands, creating a shock that propagates through the body, resulting in fragmentation and dispersal. The structure of the asteroid was modeled with a linear strength model and a core yield strength of 14.6 MPa. The mass-averaged speed of the fragments after 6 s was near 50 m/s, with a peak near 30 m/s. A three-dimensional fragment distribution was constructed from the hydrodynamics model by rotating the position, speed, and mass of each zone to a randomly assigned azimuth about the axis of symmetry. While the material representations used have been tested in a terrestrial environment, there are low-density objects, like Mathilde, where crater evidence suggests a very porous regolith with efficient shock dissipation. Shock propagation may be less efficient in such porous material, generally reducing the net impulse from a given amount of energy coupled into the surface. More research in this area is needed to understand the limits of very low porosity.

Preliminary results for the above model (Ap300) at 15 days before impact indicate that only 3% of the initial mass impacts the Earth, even for such a very short propagation time after intercept. The impact mass can be further reduced to 0.2% if the intercept direction is aligned along the inward or outward direction of the orbit, i.e., perpendicular to NEO's orbital flight direction. Such a sideways push is known to be an optimal when a target NEO is in the last terminal orbit before the impact. Furthermore, in a real situation, we will probably employ a larger NED (e.g., 1–2 Mt instead of 300 kt) against a 300-m class target asteroid.

For a larger 1-km NEO, two basic models (M97 and M20e) were also described in [17]. Both models sourced 900 kt into a cubic surface region of the same 1-km diameter object, with an initial mass of 1.047×10^9 ton. The difference is that M97 was a finely zoned model. Approximately 20 s after the energy deposition, M97 had 31,984 zones of asteroid material for 9.6732×10^8 ton, 92.8% of the initial mass. The missing 7.2% was ejected from the mesh at high speed prior to the end of the hydrodynamics simulation.

Expanding upon these nuclear fragmentation models (Ap300, M97, and M20e), the ADRC is currently developing high-fidelity nuclear fragmentation models including the effects of hypervelocity impact crater condition uncertainties (caused by the fore body KEI spacecraft) on the dispersal velocity distribution and the size of each fragment, to develop optimal intercept/impact strategies for robust nuclear fragmentation and dispersion [18,19]. The fore body impacts the asteroid surface first, creating a large crater, followed by the aft body carrying nuclear explosives, which penetrates to a depth of several meters. The "static" nuclear subsurface blast models used in [17] need to be refined to assess overall mission robustness in employing such impulsive, high-energy nuclear subsurface explosions in the face of various physical modeling uncertainties, especially those caused by the initial kinetic-energy impact crater conditions created by the fore body KEI spacecraft.

Some preliminary results of hypervelocity impact modeling and simulation using a GPU (Graphics Processing Unit) accelerated hydrodynamics code, which is being developed at the ADRC, are discussed in [18,19]. Further study results for the HNI system concept can be found in [20]. A baseline HNIS system is illustrated in

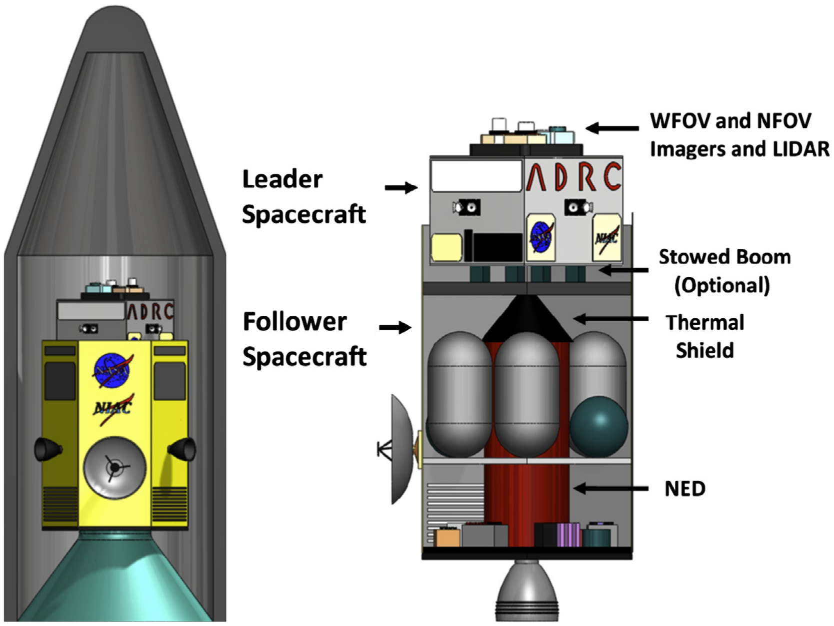

Fig. 9. A baseline HNI system [20].

Fig. 9. A Delta II-class launch vehicle in conjunction with an upper stage can be used to launch a smaller HNI system carrying a 300-kg NED payload [20,21]. Likewise, a Delta IV Heavy launch vehicle class can deliver a scaled-up version of the HNI system carrying a 1500-kg NED payload. Potential NEO candidates have been selected for a planetary defense technology (PDT) demonstration mission in [22]. Such a PDT demonstration mission is necessary to validate and verify the practical effectiveness of blending a hypervelocity kinetic impactor with a penetrated nuclear subsurface explosion [20–22].

5. Parametric characterization of modeling uncertainties

Space missions to deflect or disrupt a hazardous NEO will require accurate prediction of its orbital trajectory, both before and after a deflection/disruption event. Understanding the inherent sensitivity of mission success to *the uncertainties in the orbital elements and material properties of a target NEO* will lead to a more robust mission design, in addition to identifying the required precision for observation, tracking, and characterization of a target NEO. The unique technical challenges posed by NEO deflection/disruption dictate the level of precision needed in the physical modeling of hazardous NEOs and the identification of relevant parameters through computational/analytical/experimental studies, remote observation, and/or characterization missions. Consequently, uncertainty modeling and its parametric characterization are of current interest to the planetary defense community. The current study at the ADRC also focuses on the parametric characterization of various physical modeling uncertainties, especially for nuclear deflection/disruption missions. Because the required degree of physical modeling accuracy strongly depends on the specific mitigation mission type, the current study at the ADRC emphasizes parametric characterization of physical modeling uncertainties and their resulting orbital perturbation effects on the outcome of various nuclear deflection/disruption options, such as high- or low-altitude standoff, surface contact burst, and penetrated subsurface nuclear explosions. The effectiveness and robustness of each option in the presence of significant physical modeling uncertainties needs to be further examined.

Space missions requiring nuclear deflection/disruption of NEOs are in general concerned with: (i) robust predictability of the sufficient miss distance for a successfully deflected NEO; (ii) robust predictability of the fragments impacting the surface of the Earth (for a worst-case situation with a very short warning time); (iii) a reliable assessment of reduced impact damages due to a last minute disruption mission; and (iv) an accurate modeling of $\Delta\vec{V}$ (magnitude and direction of velocity change) within desired error bounds. Uncertainties in mass, density, porosity, material strength, and other physical parameters can substantially influence the outcome of any nuclear deflection/disruption attempt. Therefore, a detailed study is needed to characterize these uncertain parameters, especially for robust nuclear deflection/disruption mission design.

Also, we need to characterize, computationally and/or analytically, the modeling uncertainties and the resulting orbit perturbation effects in terms of effective $\Delta\vec{V}$ uncertainties and/or uncertain perturbations in orbital elements (Δa, Δe, Δi, $\Delta\Omega$, $\Delta\omega$, ΔM_0), as well as fragment velocity dispersion. In particular, the uncertainty associated with the initial dispersal velocity and mass distribution of fragments needs to be rigorously modeled and characterized for robust disruption mission design. Mutual gravitational interactions amongst the fragments also needs to be included in the high-fidelity dispersion modeling and simulation.

Finally, we need to increase communication and interaction among NEO deflection research engineers and NEO characterization research scientists through building a consensus on the necessary reliable models in the face of significant physical modeling uncertainties as well as the practical mission constraints.

6. Conclusion

A concept of using a fore body (a leader spacecraft) to provide proper kinetic-energy impact crater conditions for an aft body (a follower spacecraft) carrying nuclear explosives has been proposed in this paper as a technically feasible option for the most probable impact threat of NEOs with a short warning time (e.g., much less than 10 years). The current and planned studies at the ADRC would enable an important step forward for this area of emerging international interest, by finding the most cost-effective, reliable, versatile, and technically feasible solution to the NEO impact threat mitigation problem, which is now one of NASA's Space Technology Grand Challenges.

Acknowledgment

This research has been supported by a grant from NASA's Iowa Space Grant Consortium. The author would like to thank Dr. David Dearborn at Lawrence Livermore National Laboratory for his technical advice and support in the area of nuclear fragmentation modeling and simulation. The proposed HNI system has been selected as an NIAC (NASA Innovative Advanced Concept) Phase 1 project by the NASA Office of the Chief Technologist. The author would like to thank Dr. John (Jay) Falker, the NIAC Program Executive, for his support of the proposed HNI system research project.

References

[1] 〈http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp-letter-neo-senate.pdf〉, John Holdren, Director, the White House Office of Science and Technology Policy (OSTP), October 15, 2010.

[2] D. Dearborn, 21st Century Steam for Asteroid Mitigation, AIAA-2004-1413, 2004 Planetary Defense Conference: Protecting Earth from Asteroids, Orange County, CA, Feb. 23–26, 2004.

[3] B. Dachwald, B. Wie, Solar-Sail Kinetic Energy Impactor Trajectory Optimization for an Asteroid Deflection Mission, J. Spacecraft Rockets 44 (4) (2007) 755–764.

[4] E. Lu, S. Love, Gravitational Tractor for Towing Asteroids, Nature 438 (November (10)) (2005) 177–178.

[5] B. Wie, Dynamics and Control of Gravity Tractor Spacecraft for Asteroid Deflection, J. Guid. Control Dynam. 31 (5) (2008) 1413–1423.

[6] Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies, National Research Council, National Academy of Sciences, 2010.

[7] Effects of Nuclear Earth-Penetrator and Other Weapons, National Research Council, National Academy of Sciences, 2005.

[8] T. Gehrels (Ed.), Hazards Due to Comets and Asteroids, The University of Arizona Press, Tucson, AZ, 1994.

[9] M. Belton, et al., (Eds.), Mitigation of Hazardous Comets and Asteroids, Cambridge University Press, 2005.

[10] B. Kaplinger, B. Wie, J. Basart, Analysis of nuclear standoff explosions for deflecting near-Earth objects, Proceedings of 1st IAA Planetary Defense Conference, Granada, Spain, April 2009.

[11] V.V. Rodionov, et al., Nuclear Means for Affecting Near-Earth Objects, Russia, 1997. 〈http://csc.ac.ru/news/1997_1/ae29.pdf〉.

[12] V.G. Chistov, et al., Nuclear Explosive Deep Penetration Method into Asteroid, Russia, 1997. 〈http://csc.ac.ru/news/1997_1/ae31.pdf〉.

[13] S. Wagner, A. Pitz, D. Zimmerman, B. Wie, Interplanetary Ballistic Missile (IPBM) System Architecture Design for Near-Earth Object Threat Mitigation, Paper No. IAC-09-D1.1.1, 60th International Astronautical Congress, Daejeon, Korea, October 12-16, 2009.

[14] S. Wagner, B. Wie, Analysis and Design of Fictive Post-2029 Apophis Intercept Mission for Nuclear Disruption, AIAA 2010-8375, AIAA/AAS Astrodynamics Specialist Conference, Toronto, Canada, August 2–5, 2010.

[15] M. Hawkins, A. Pitz, B. Wie, J. Gil-Fernndez, Terminal-Phase Guidance and Control Analysis of Asteroid Interceptors, AIAA 2010-8348.

[16] M. Hawkins, Y, Guo, B. Wie, Guidance Algorithms for Asteroid Intercept Missions with Precision Targeting Requirements, AAS 11-531, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, August 1-4, 2011.

[17] B. Wie, D. Dearborn, Earth-Impact Modeling and Analysis of a Near-Earth Object Fragmented and Dispersed by Nuclear Subsurface Explosions, AAS 10-137, 20th AAS/AIAA Space Flight Mechanics Meeting, San Diego, CA, Feb. 15–17, 2010.

[18] B. Kaplinger, B. Wie, D. Dearborn, Preliminary Results for High-Fidelity Modeling and Simulation of Orbital Dispersion of Asteroids Disrupted by Nuclear Explosives, AIAA 2010-7982, AIAA/AAS Astrodynamics Specialist Conference, Toronto, Canada, August 2–5, 2010.

[19] B. Kaplinger, B. Wie, D. Dearborn, NEO Nuclear Fragmentation and Dispersion Modeling and Simulation, 2011 IAA Planetary Defense Conference, Bucharest, Romania, May 9–12, 2011.

[20] A. Pitz, B. Kaplinger, B. Wie, D. Dearborn, A Hypervelocity Nuclear Interceptor System (HNIS) for Optimal Disruption of Near-Earth Objects, AAS 12-225, AAS/AIAA Space Flight Mechanics Meeting, 2012.

[21] G. Vardaxis, A. Pitz, B. Wie, Conceptual Design and Analysis of Planetary Defense Technology Demonstration Mission, AAS 12-128, AAS/AIAA Space Flight Mechanics Meeting, 2012.

[22] T. Winkler, S. Wagner, B. Wie, Optimal Target Selection for Planetary Defense Technology (PDT) Demonstration Mission, AAS 12-226, AAS/AIAA Space Flight Mechanics Meeting, 2012.